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HEAT-TRANSFER MEASUREMENTS ON A 5-DEG SHARP CONE USING INFRARED SCANNING AND ON-BOARD DISCRETE SENSOR TECHNIQUES

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Heat transfer data were obtained in hypersonic flow on a slender 5-deg half angle cone to evaluate the accuracy and test procedure of an infrared thermal mapping technique. Data were also obtained using discrete on board measurements for comparative purposes.

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NOMENCLATURE

ALPHA-MODEL, α	Model angle of attack, deg
b	Model thermocouple section skin thickness, in.
BETA (0.9TO), β	Semi-infinite slab parameter $\beta = \frac{H(TAW)\sqrt{\Delta t}}{\sqrt{\rho c k}}$ for this test, data were reduced with TAW defined as 0.9TO
c_p	Specific heat of model material, $\frac{Btu}{lbm\text{-}°R}$
CONFIGURATION	Model configuration code number
DELTA TIME, Δt	Time model was exposed to flow before IR digitizing, sec
DTW/DT	Rate of change of temperature with respect to time
GROUP	Identification number for each tunnel injection
H(TAW)	Model heat-transfer coefficient based on adiabatic wall temperature, Btu/ft^2-sec-°R
H(TO)	Model heat-transfer coefficient based on tunnel stilling chamber temperature, TO, Btu/ft^2-sec-°R
H(0.9TO)	Model heat-transfer coefficient based on 0.9TO, Btu/ft^2-sec-°R
HRFR, HREF	Reference heat-transfer coefficient based on Fay-Riddell theory, Btu/ft^2-sec-°R $= \left[\frac{8.172(P01)^{0.5}(MU\text{-}O)^{0.4}(1-(P\text{-}INF)/P01)^{0.25}}{(RN)^{0.5}\ (TO)^{0.15}}\right] \times \left[0.2235 + 0.0000135\ (TO + 560)\right]$ where P01 - stagnation pressure downstream of a normal shock, psia MU-O = air viscosity based on TO, lbf-sec/ft^2 RN = reference nose radius set at 1.0 ft

k	Model material or coax gage thermal conductivity, Btu/ft-sec-°R
MACH, M_∞	Free-stream Mach number
MU-INF	Free-stream viscosity, lbf-sec/ft^2
PCK1/2	see $\sqrt{\rho c_p k}$
P-INF	Free-stream pressure, psia
PO	Tunnel stilling chamber pressure, psia
QDOT	Heat transfer rate, Btu/ft^2-sec
Q-INF	Free-stream dynamic pressure, psia
RE/FT	Free-stream unit Reynolds number, ft^{-1}
RB	Model base radius, in.
RN	Model nose radius, in.
RHO-INF	Free-stream density, slugs/ft^3
ROLL-MODEL	Model roll, deg
S	Lateral surface distance along model, measured from centerline (Fig. 2), in.
SF	Gardon gage scale factor, Btu/ft^2-sec/mv
SF CORR	Corrected Gardon gage scale factor, Btu/ft^2-sec/mv
TAW	Adiabatic wall temperature, °R
T/C	Thermocouple
TGE, TCASE	Gardon gage edge temperature, °R
TW, TWALL	Corrected gage surface temperature or model wall temperature, °R
$\bar{T}$	Temperature difference (TW-TI), °R
TI	Initial model wall temperature before model is injected into the flow, °R
T-INF	Free-stream temperature, °R
TO	Tunnel stilling chamber temperature, °R
t	Time
V-INF	Free-stream velocity, ft/sec

X	Axial distance from nose of model (Fig. 2), in.
α	Model angle of attack, deg
ρ	Model material density, lbm/ft^3
$\sqrt{\rho c_p k}$	Square root of the product of the model density, specific heat and thermal conductivity, $Btu/ft^2\text{-}sec^{1/2}\text{-}sec°R$

SUBSCRIPTS

RT	Room temperature

1.0 INTRODUCTION

The work reported herein was conducted by the Arnold Engineering Development Center (AEDC), Air Force Systems Command (AFSC), under Program Element 65807F, Control Number 9R02-15-8, at the request of AEDC, Director of Test Engineering, Research Division, AEDC/DOTR for the von Karman Facility Aerodynamics Instrumentation Branch, VKF/ADI. The AEDC/DOTR project monitor was Mr. Marshall Kingery and the VKF/ADI project monitor was Mr. A. H. Cortner. The results were obtained by ARO, Inc., AEDC Division (a Sverdrup Corporation Company), operating contractor for the AEDC, AFSC, Arnold Air Force Station, Tennessee. The test was conducted in the von Karman Gas Dynamics Facility (VKF), Hypersonic Wind Tunnel (B) on October 17, 1978 under ARO Project No. V41B-Y5.

This test was conducted in support of ARO technology project V32A-P4. The purpose was to evaluate, under actual wind tunnel conditions, modifications which had been incorporated into the VKF infrared (IR) data system. The major addition which had been made to the IR system was the capability to digitize and acquire multiple data frames from the IR camera during a single data acquisition sequence. Previously (Ref. 1) only one data frame could be obtained each time the system was activated. This meant in effect that only a single frame was recorded each time a model was injected into the tunnel. Addition of the multiple frame capability introduces several possibilities for improvements in the quality and quantity of the data from the IR system. Infrared scanning data were obtained on thin skin metal model sections as well as standard insulative sections to evaluate different data reduction techniques.

By using on-board sensors, this test also provided an opportunity to obtain further data comparisons between the IR system and other heat-transfer measurement techniques.

The test was conducted in the 50-in. Hypersonic Wind Tunnel (B) at a free-stream Mach number of 8 and free-stream unit Reynolds numbers near 1.8×10^6 and 3.7×10^6 per foot. Angles-of-attack of -5-, 0-, and 5-deg were run at roll angles of 0 and 180-deg. In addition to the IR system, model instrumentation included thermocouples on thin skin panels, Gardon heat-transfer gages, and coaxial thermocouple gages.

Inquiries to obtain copies of the test data should be directed to AEDC/DOTR, Arnold Air Force Station, TN 37389. A microfilm record has been retained in the VKF at AEDC.

2.0 APPARATUS

2.1 TEST FACILITY

Tunnel B (Fig. 1) is a closed circuit hypersonic wind tunnel with a 50-in. diam test section. Two axisymmetric contoured nozzles are available to provide Mach numbers of 6 and 8 and the tunnel may be operated continuously over a range of pressure levels from 20 to 300 psia at Mach number 6, and 50 to 900 psia at Mach number 8, with air supplied by the VKF main compressor plant. Stagnation temperatures sufficient to avoid air liquefaction in the test section (up to 1350°R) are obtained through the use of a natural gas fired combustion heater. The entire tunnel (throat, nozzle, test section, and diffuser) is cooled by integral, external water jackets. The tunnel is equipped with a model injection system, which allows removal of the model from the test section while the tunnel remains in operation. A description of the tunnel may be found in the Test Facilities Handbook (Ref. 2).

2.2 TEST ARTICLE

The model used in this test was a 5-deg half-angle sharp and blunt cone with a 7-in. base diameter (Fig. 2). Bluntness ratio for the blunt cone configuration was 0.107. One sharp nose had machined roughness of 0.030 inches located as shown in Fig. 2. The majority of the investigation used a sharp clean nose configuration. The removable insert at the aft end of the model made it possible to use several different instrumentation techniques to measure the heat-transfer rate on the cone. Two insulated panels (Teflon® and RTV-60®) were fabricated to use with the IR thermal mapping system. The requirement for an insulative material for use with the IR thermal mapping technique is discussed in Ref. 1. A stainless steel panel was fabricated and instrumentated with thermocouples, Gardon gages, and coaxial surface thermocouple gages. Instrumentation type and location is identified in Fig. 2 and Table 1. The model forecone was instrumented with coax surface thermocouple gages which were filed to provide a smooth aerodynamic surface. All three inserts were carefully machined to eliminate model surface discontinuities. A photograph of the model installed in Tunnel B is shown in Fig. 3.

2.3 TEST INSTRUMENTATION

2.3.1 Test Conditions

Tunnel B stilling chamber pressure is measured with a 200- or 1000-psid transducer referenced to a near vacuum. Based on periodic comparisons with secondary standards, the accuracy (a bandwidth which includes 95-percent of residuals, i.e. 2σ deviation) of the transducers is estimated to be within ±0.25 percent of pressure or ±0.3 psi, whichever is greater for the 200-psid range and ±0.25 percent of pressure or ±0.8 psi, whichever is greater for the 1000 psid range. Stilling chamber temperature measurements are made with Chromel®-Alumel® thermocouples which have an uncertainty of ±(1.5°F + 0.375 percent of reading).

2.3.2 Test Data

The thermal mapping technique which uses the IR scanning system is fully described in Ref. 1. The discrete gage methods are described in Ref. 3. Data reduction procedures for all instrumentation methods are given in Section 3.2.

3.0 TEST DESCRIPTION

3.1 TEST CONDITIONS AND PROCEDURES

3.1.1 General

A summary of the nominal test conditions at each Mach number is given below.

MACH	PO, psia	TO, °R	P-INF, psia	RE x 10^{-6}/ft
8.0	870	1360	0.089	3.7
8.0	397	1300	0.042	1.8

A test summary showing all configurations tested and the variables for each data group is presented in Table 2.

In the VKF continuous flow wind tunnels (A, B, C), the model is mounted on a sting support mechanism in an installation tank directly underneath the tunnel test section. The tank is separated from the tunnel by a pair of fairing doors and a safety door. When closed, the fairing doors, except for a slot for the pitch sector, cover the opening to the tank and the safety door seals the tunnel from the tank area. After the model is prepared for a data run, the personnel access door to the installation tank is closed, the tank is vented to the tunnel flow, the safety and fairing doors are opened, and the model is injected into the airstream, and the fairing doors are closed. After the data are obtained, the model is retracted into the tank and the sequence is reversed with the tank being vented to atmosphere to allow access to the model in preparation for the next run. The sequence is repeated for each configuration change.

3.2 DATA REDUCTION

For each group, the tabulated data begins with a listing of tunnel conditions and model information required to characterize the run and use the data. Following this the model data are presented.

The Gardon gages used in the model are direct reading heat flux transducers whose output may be converted to heating rate by means of a laboratory-obtained scale factor, i.e.

$$QDOT = SF \times (\text{gage millivolt output}) \qquad (1)$$

The scale factor has been found to be a function of the gage temperature, and the data reduction procedure uses a corrected value given by

$$\begin{aligned}SFCORR = SF\ [0.985693 &+ (2.41342 \times 10^{-4})TGE \\ &-(1.13235 \times 10^{-6})(TGE)^2 + (1.07481 \times 10^{-9})(TGE)^3 \\ &-(3.92156 \times 10^{-13}(TGE)^4]\end{aligned} \tag{2}$$

where TGE is the temperature measured by a thermocouple attached to the edge of the sensing disk. The gage surface temperature is given by

$$TW = TGE + 0.75\ \Delta T \tag{3}$$

where $\Delta T = K \times$ (gage millivolt output)

and K is a laboratory-obtained temperature factor

The heat-transfer coefficient is calculated

from

$$H(TO) = \frac{QDOT}{TO - TW} \tag{4}$$

and

$$H(0.9TO) = \frac{QDOT}{0.90TO-TW} \tag{5}$$

The reduction of thin-skin thermocouple data normally involves only the calorimeter heat balance which in coefficient form is:

$$H(TAW) = \rho bc_p \frac{DTW/DT}{TAW-TW} \tag{6}$$

For this test a value of 0.90 TO (based on experience) was selected for TAW and equation (6) can be written

$$H(0.90TO) = \rho bc_p \frac{DTW/DT}{0.90TO-TW} \tag{7}$$

Radiation and conduction losses are neglected in this heat balance and data reduction simply requires evaluation of DTW/DT from the temperature-time data and determination of model material properties. For the present tests, radiation effects were negligible; however, conduction effects can be significant in several regions of the model. To permit identification of these regions and to improve evaluation of the data, the following procedure was used.

Separation of variables and integration of equation (7) assuming constant ρ, b, c_p, and TO yields

$$\frac{H(0.90TO)}{\rho bc_p}(t - t_i) = \ln\left[\frac{0.90TO - TI}{0.90TO - TW}\right] \tag{8}$$

Differentiation of Eq. (8) with respect to time gives

$$\frac{H(0.90TO)}{\rho b c_p} = \frac{d}{dt} \ \ell n \left[\frac{0.90TO - TI}{0.90TO - TW} \right] \tag{9}$$

Since the left side of Eq. (9) is a constant, plotting $\ell n \left[\frac{0.90TO - TI}{0.90TO - TW} \right]$ versus time will give a straight line if <u>conduction is negligible</u>. Thus, deviation from a straight line can be interpreted as conduction effects.

The data were evaluated in this manner, and generally a linear portion of the curve was used for all thermocouples. A linear least-square curve fit of ℓn [0.90TO - TI)/(0.90TO-TW)] versus time was applied to the data. Data reduction was started as soon as the model reached the tunnel centerline and the curve fit extended for a time span which was a function of the heating rate, as shown in the following list.

Range	No. of Points (Fit Length)
$\frac{DTW}{DT} > 32$	5
$16 < \frac{DTW}{DT} \leq 32$	7
$8 < \frac{DTW}{DT} \leq 16$	9
$4 < \frac{DTW}{DT} \leq 8$	13
$2 < \frac{DTW}{DT} \leq 4$	17
$1 < \frac{DTW}{DT} \leq 2$	25
$\frac{DTW}{DT} \leq 1$	41

The above time spans were generally adequate to keep the evaluation of the right side of Eq. (9) within the linear region. The linearity of the fit was substantiated by visual inspection of the cases in question. This visual check of the data was done on the VKF graphics terminal. Strictly speaking, the value of c_p for the material was not constant, and the following relation

$$c_p = 0.0882 + (6.0 \times 10^{-5})\ TW, \text{ (13-8 stainless steel) Btu/lbm-°R} \tag{10}$$

was used with the value of TW at the midpoint of the curve fit. The maximum variation of c_p over any curve fit was less than 0.5 percent. The value of density used for 13-8 stainless steel was 482.1 lbm/ft^3, and the skin thickness, b, was 0.029 in.

The coaxial gage provides measurement of the surface temperature of the gage-model composite which is assumed to be a homogenous, one-dimensional, semi-infinite solid. Of course, the gages and the model wall are of finite thickness (about 0.3 in.), and the semi-infinite solid assumption is valid for a maximum of about 2 seconds after the model reaches tunnel centerline. However, this time is adequate for data acquisition and the above assumptions are used to compute the heat flux at the model surface.

For one-dimensional heat-flow into a semi-infinite solid, the surface temperature difference, $\overline{T}(t)$, and the surface heat flux, QDOT(t), are related by the following expression (Ref. 4):

$$QDOT(t) = \frac{(\rho c_p k)^{\frac{1}{2}}}{\pi^{\frac{1}{2}}} \left[\frac{\overline{T}(t)}{t^{\frac{1}{2}}} + \frac{1}{2} \int_o^t \frac{\overline{T}(t) - \overline{T}(\tau)}{(t - \tau)^{3/2}} d\tau \right] \tag{11}$$

where τ is a dummy variable of integration and $\overline{T}$ is (TW-TI). Cook and Felderman (Ref. 4) have developed a numerical technique for the solution of this equation which does not involve assumptions about the nature of the input function. The Cook and Felderman expression has been reduced to a "short form" solution at the VKF with resulting equation:

$$QDOT(t_n) = \frac{2C(t_n)}{\pi^{\frac{1}{2}}} \sum_{j=1}^{n} \frac{\overline{T}(t_j) - \overline{T}(t_{j-1})}{t_j - t_{j-1}} \left[\sqrt{t_n - t_{j-1}} - \sqrt{t_n - t_j} \right] \tag{12}$$

where

t = time from start of model injection cycle, sec (at any time t_n, n samples of data have been taken)

t_j = time corresponding to data sample number j, sec

t_n = time at which the heat-transfer rate QDOT(t_n) was calculated, sec

$C(t_n)$ = square root of the product of gage density, specific heat and conductivity, $(\rho c_p k)^{\frac{1}{2}}$, Btu/ft^2-sec$^{\frac{1}{2}}$-°R

The lumped thermal parameter $(\rho c_p k)^{\frac{1}{2}}$ was previously determined as a linear function of temperature. For this test each gage was individually calibrated at room temperature to evaluate the value $(\rho c_p k)^{\frac{1}{2}}_{RT}$ and the linear relationship was combined with this value to obtain

$$(\rho c_p k)^{\frac{1}{2}} = (\rho c_p k)^{\frac{1}{2}}_{RT} + [-0.28141 + (0.000526)TW]. \tag{13}$$

The actual value of $C(t_n)$ was defined from the average temperature value as

$$C(t_n) = (\rho c_p k)^{\frac{1}{2}}_{RT} + \left[-0.28141 + 0.000526\left(\frac{TW + TI}{2}\right)\right]. \tag{14}$$

The expression defined in equation (12) was used in the present data reduction procedure. The solution of Eq. (12) is affected by noise in the signal which is used to compute $\bar{T}$. To improve accuracy in the final result, values of QDOT were averaged for seven loops starting one second after the model reached centerline. The average value of surface temperature over the same period was used to calculate the heat-transfer coefficients using Eq. 4 or 5.

Reduction of infrared data is based on the assumption that the surface temperature history is that of a homogeneous, semi-infinite slab subjected to an instantaneous and constant heat-transfer coefficient. The heat transfer coefficient H(0.9TO) is then related to the model surface temperature through the relationships.

$$\frac{TW - TI}{TAW - TI} = 1 - e^{\beta^2} \text{ erfc } \beta \tag{15}$$

where

$$\beta = H(TAW)\ \sqrt{\Delta t}/\sqrt{\rho c_p k} \tag{16}$$

The method by which the model surface temperature is inferred from the measured emitted radiation is given in Ref. 1.

3.3 UNCERTAINTY OF MEASUREMENTS

3.3.1 General

The accuracy of the basic measurements (PO and TO) was discussed in Section 2.3. Based on repeat calibrations, these errors were found to be

$$\frac{\Delta PO}{PO} = 0.003 = 0.3\%, \quad \frac{\Delta TO}{TO} = 0.004 = 0.4\%$$

Uncertainties in the tunnel free-stream parameters and the heat transfer coefficients were estimated using the Taylor series method of error propagation, Eq. (17),

$$(\Delta F)^2 = \left(\frac{\partial F}{\partial X_1}\Delta X_1\right)^2 + \left(\frac{\partial F}{\partial X_2}\Delta X_2\right)^2 + \left(\frac{\partial F}{\partial X_3}\Delta X_3\right)^2 \dots + \left(\frac{\partial F}{\partial X_n}\Delta X_n\right)^2 \tag{17}$$

where ΔF is the absolute uncertainty in the dependent parameter $F = f(X_1, X_2, X_3 \ldots X_n)$ and X_n are the independent parameters (or basic measurements). ΔX_n are the uncertainties (errors) in the independent measurements (or variables).

3.3.2 Test Conditions

The accuracy (based on 2σ deviation) of the basic tunnel parameters, PO and TO, (see Section 2.3) and the 2σ deviation in Mach number determined from test section flow calibrations were used to estimate uncertainties in the other free-stream properties using Eq.(17). The computed uncertainties in the tunnel free-stream conditions are summarized in the following table.

	Uncertainty, (±) percent of actual value		
MACH	MACH	P-INF	RE/FT
8.0	0.4	2.5	1.2

3.3.3 Test Data

The uncertainty in model angle of attack (ALPHA) and sideslip, as determined from calibrations and consideration of the possible errors in model deflection calculations, is estimated to be ±0.25 deg and ±0.10 deg, respectively.

Estimated uncertainties for the individual terms in the thin-skin data reduction equations were used in the Taylor series method of error propagation to obtain uncertainty in values of heat-transfer coefficient as given below:

Parameter	Range	Nominal Uncertainty, percent
(Heat Transfer Coefficient)	10^{-4}	±10
	10^{-3}	± 7
	10^{-2}	± 5

The total uncertainty in the heat transfer coefficient for Gardon and coax heat gage measurements is:

Parameter	Range, Btu/ft^2-sec	Nominal Uncertainty, percent
(Heat Transfer Rate)	Co-ax $\geq$ 0.5*	±6
	Gardon $\geq$ 0.02*	±6

Data precision of heat transfer coefficients obtained using the IR Scanning method has not been well established since the system is

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* The majority of the present results were greater than these values.

still under development. It has been determined that the precision is highly dependent on the flow environment (Tunnel conditions) and the absolute level of the model surface temperature. The present tests were at flow conditions and temperature levels which produced nominal uncertainty of ±13 percent.

4.0 DATA PACKAGE PRESENTATION

One of the primary objectives of this test was to compare the heat transfer coefficient deduced from several instrumentation techniques. A sharp cone model was purposely selected because precise math models are available for this geometry. The analytic solution of Ref. 5 was used to provide a baseline comparison for the present measurements. Figure 4 is such a comparison of typical data with this analytic solution.

A sample tabulation of infrared and on-board discrete measurements is presented in Appendix III. Data nomenclature corresponds to the nomenclature at the beginning of this report. A complete set of data tabulations and photographs was included in the Final Data Package for this project.

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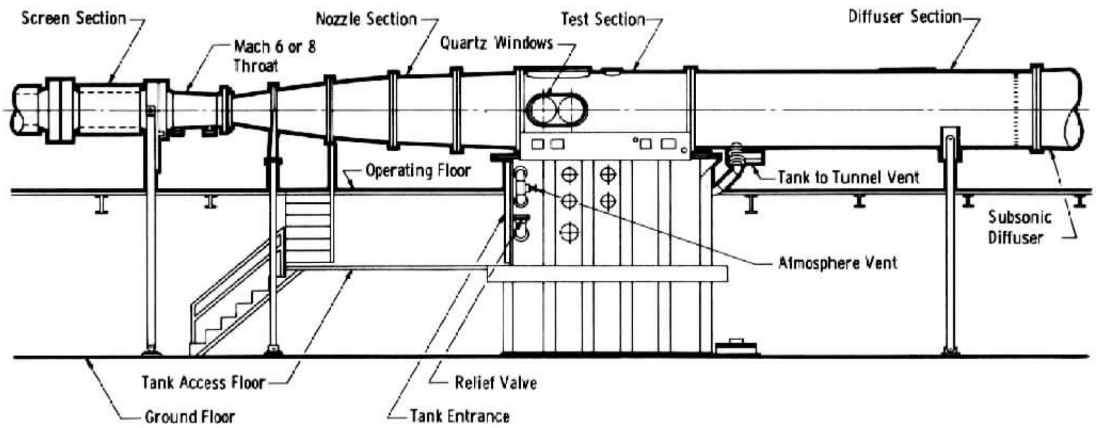
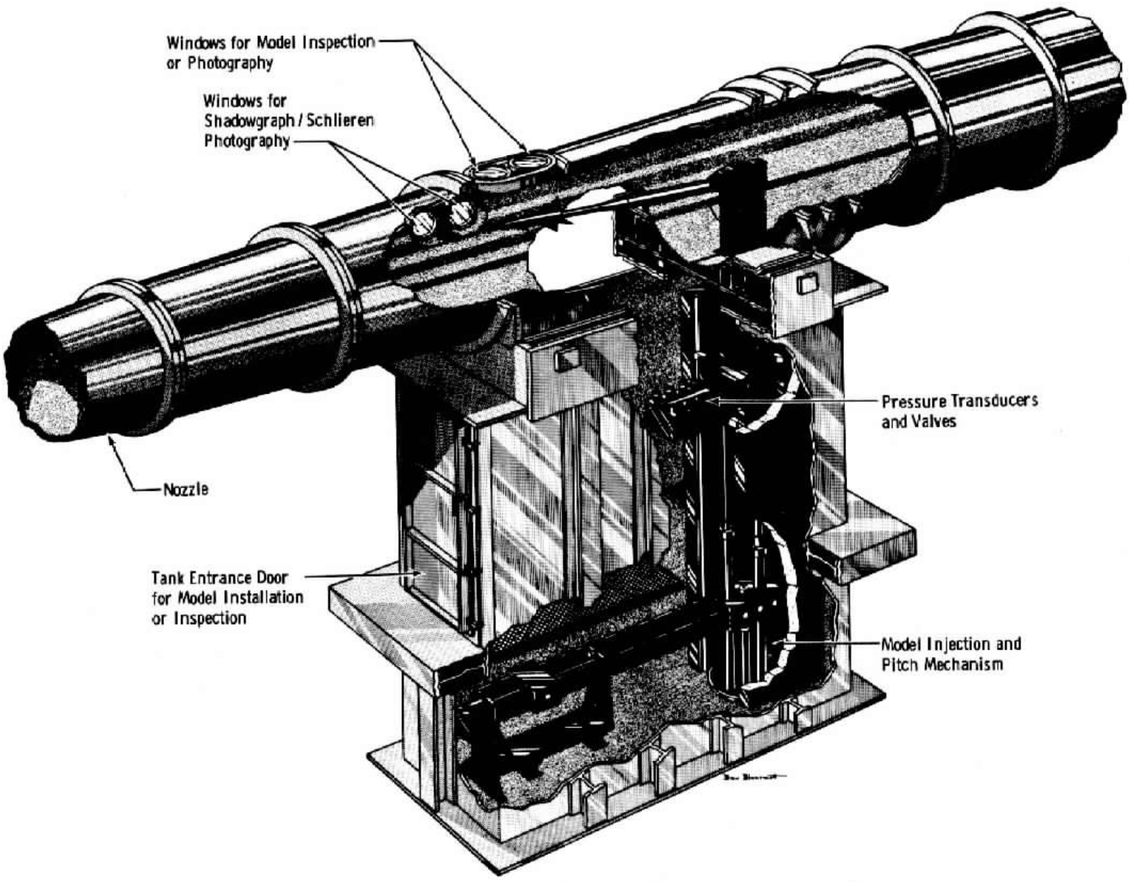
APPENDIX I

ILLUSTRATIONS



a. Tunnel assembly



b. Tunnel test section
Fig. 1. Tunnel B

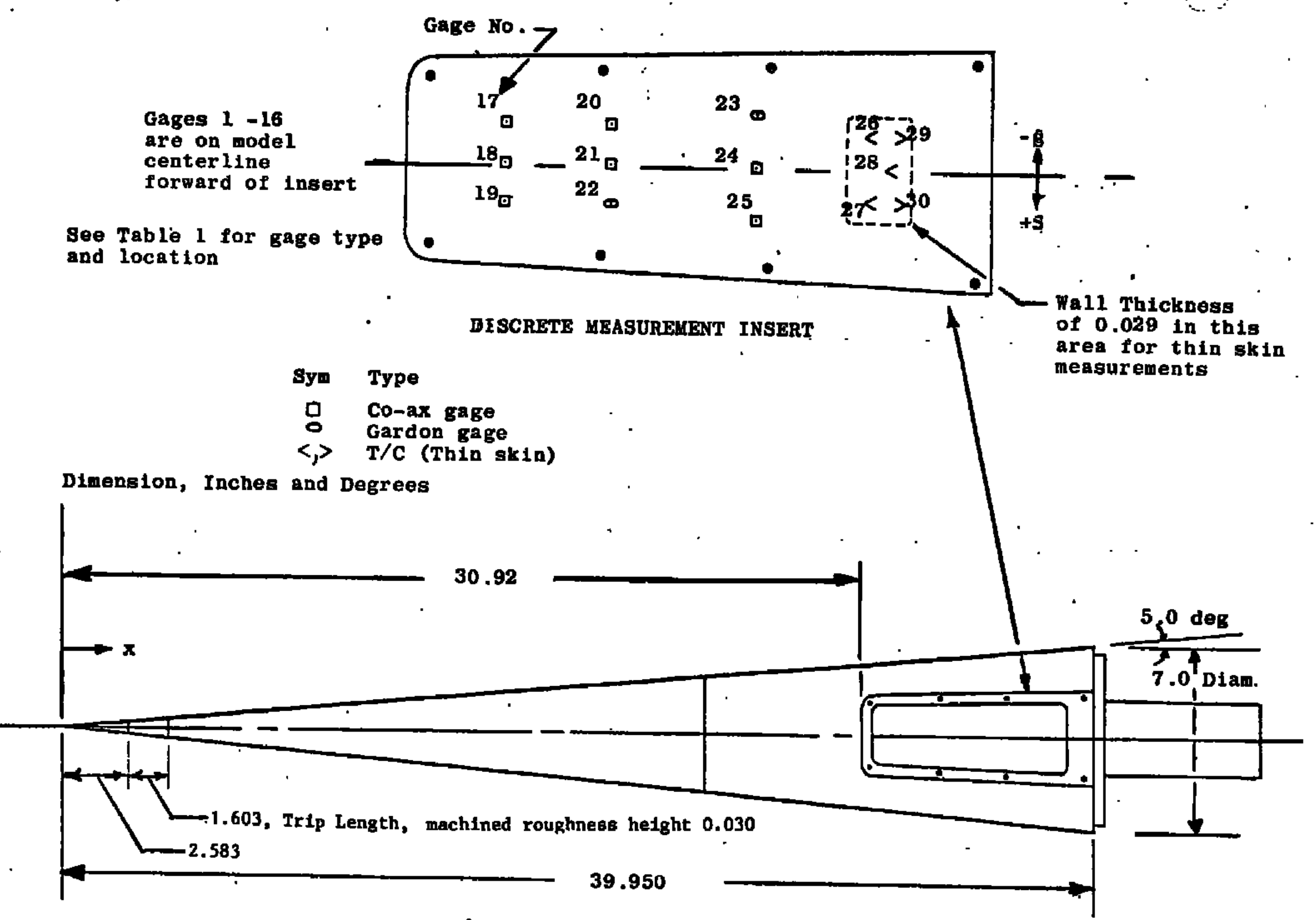


Fig. 2 Sketch of the Standard Heat Transfer Cone Model

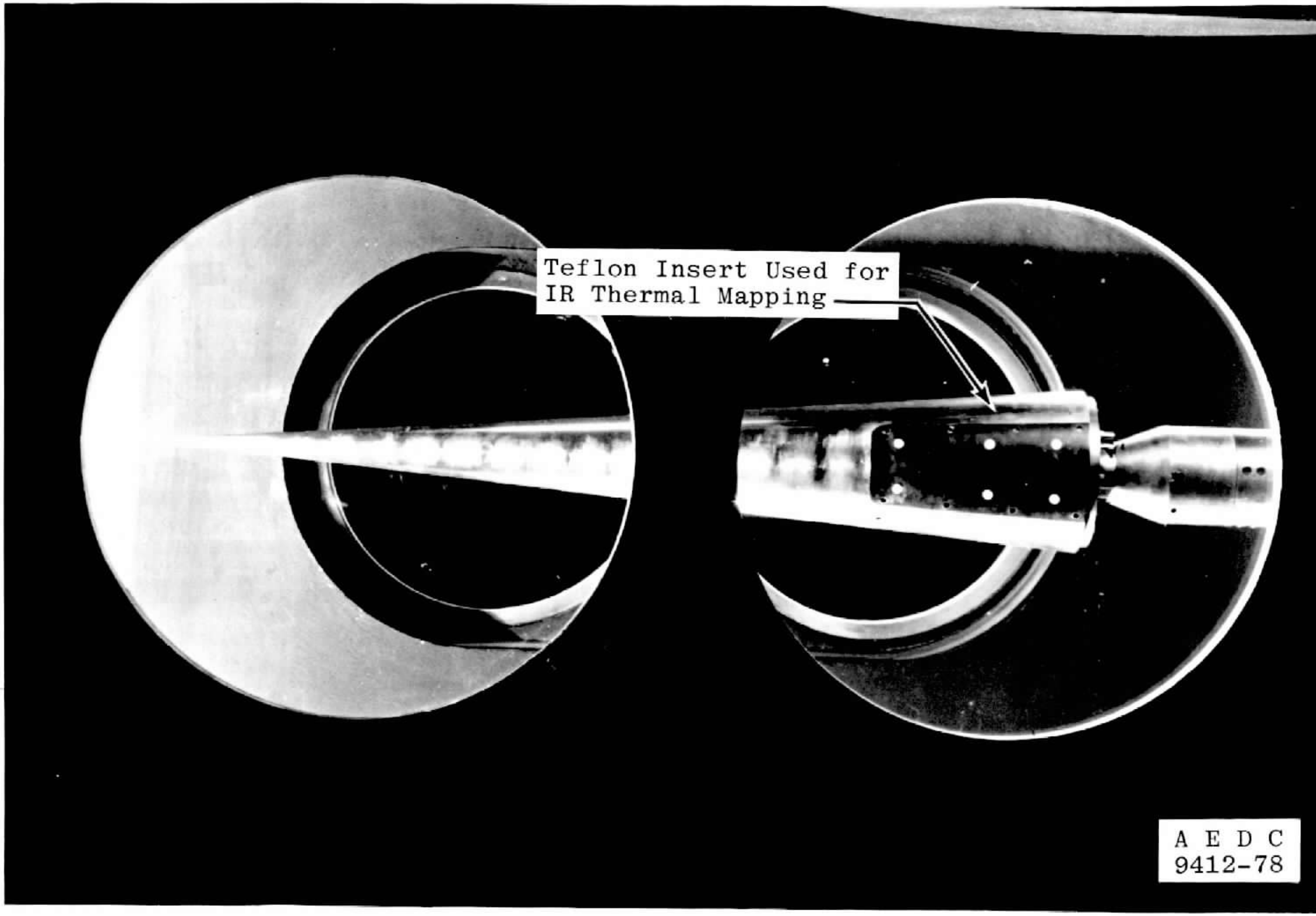


Figure 3. Photograph of the Standard Heat Transfer Cone Model Installed in Tunnel B

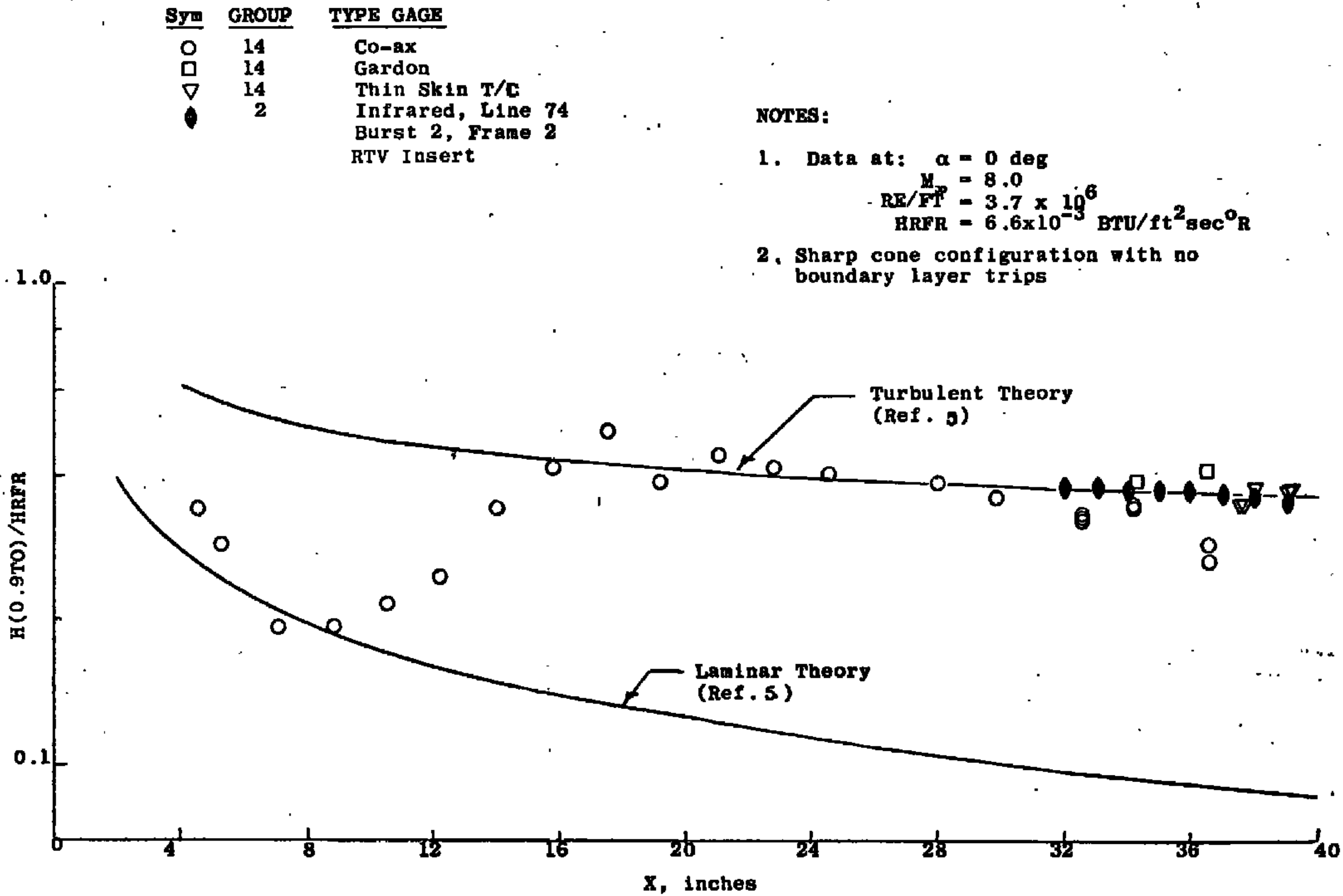


Fig. 4 Typical Data Comparison with Analytic Results

APPENDIX II

TABLES

TABLE 1

MODEL INSTRUMENTATION TYPE AND LOCATION

Gage No.	Model Location X, inches	Model Location S, inches	Type Gage	Comments
1	4.50	0	Coax	Gages on Model Forecone
2	5.25			Center Line (Fig. 2)
3	7.00			
4	8.75			
5	10.50			
6	12.25			
7	14.00			
8	15.75			
9	17.50			
10	19.25			
11	21.00			
12	22.75			
13	24.50			
14	26.25			
15	28.00			
16	29.75	0		
17	32.50	-0.51		Gages on Discrete Instrumenta-
18	32.50	0		tion Panel (Fig. 2)
19	32.50	+0.52	Coax	
20	34.20	-0.54	Coax	
21	34.20	0	Coax	
22	34.20	+0.54	Gardon	
23	36.50	-0.57	Gardon	
24	36.50	0	Coax	
25	36.50	+0.57	Coax	
26	37.50	-0.50	Thermocouple	
27	37.50	+0.50		
28	38.00	0		
29	38.50	-0.65		
30	38.50	+0.60		

TABLE 2

TEST SUMMARY

GROUP	RN/RB	INSERT	TRIPS	RE/FT x 10^{-6}	ALPHA MODEL,DEG	ROLL MODEL,DEG	COMMENTS
2	0	RTV	None	3.70	0.04	0	25 frames at Δt = 0.50 sec
3	0			3.73	0.02		Repeat of Group 2
4	0			3.76	5.00		Leeward data, 25 frames at Δt = 0.50 sec
5	0			3.79	-4.98		Windward data, 25 frames at Δt = 0.50 sec
6	0			3.75	-4.99		Repeat of Group 5, 5 frames
7	0.107			3.75	-5.02		Blunt cone, 5 frames
8	0.107			3.76	0.02		Blunt cone, 25 frames
9	0.107	RTV		3.77	5.07		Blunt cone, 25 frames
10	0	Instrumented		3.77	0	180	Discrete meas. data, 14 frames at Δt = 1.0 sec
11	0			3.77	0	180	Repeat of Group 10
12	0			3.75	+5.06		No IR data obtained
13	0			3.75	-4.93		8 frames at Δt = 0.50 sec
14	0			3.77	0		No IR data obtained
16 & 17	0	RTV with shock generator		3.79	0		Study of sharp gradients, multiple frames at Δt = 0.0625 sec
18	0	Teflon		1.82	0		Low Reynolds No. data, 25 frames
19	0	Teflon		1.82	0	180	Repeat of 18 with one frame
20	0	RTV		1.83	0	0	Ten frames digitized, Δt = 1 sec
21	0	RTV	30 mil	1.81	0	0	Trip study, 25 frames

APPENDIX III

SAMPLE TABULATED DATA

ARO, INC., AEDC DIVISION
A SVERDRUP CORPORATION COMPANY
VON KARMAN GAS DYNAMICS FACILITY (VKF)
ARNOLD AIR FORCE STATION, TENNESSEE
AEDC/DOTR AERODYNAMIC HEATING
PROJECT V41B-Y5

DATE COMPUTED 31-OCT-78
TIME COMPUTED 07:20
DATE RECORDED 19-OCT-78
TIME RECORDED 1: 8: 7

RTV INSERT

GROUP	CONFIGURATION	BURST	FRAME	ALPHA-MODEL DEG	ROLL-MODEL DEG	PCK1/2
8	N12.5T000	5	5	0.02	0.02	0.044

MACH	PO(PSIA)	TO(DEG R)	T-INF DEG R	P-INF PSIA	V-INF FT/SEC	RHO-INF SLUGS/FT3	MU-INF LB-SEC/FT2	RE/FT FT-1	HRFR BTU/FT2-SEC-R	INITIAL TEMP DEG R
8.00	871.78	1350.67	97.87	0.0893	3880.	0.763E-04	0.788E-07	0.376E+07	0.657E-02	538.7

IR CAMERA INFORMATION		TIME RECORDS		REFERENCE TARGET INFORMATION		DIGITAL DATA AREA PRINTOUT LOCATION
IR REF PLATE TCS	527.509 527.687 526.839 517.749 526.839				526.616	527.018
MOUNTING LOCATION	381	LIFT OFF	0.00	TCR5	526.84	LINE 60 THROUGH 88
F STOP	1.8	CENTER LINE	2.72	TCR6	1050.87	POINT 1 THROUGH 76
LENS-DEG	15					
SENSITIVITY	200.					
BLACK LEVEL VOLTAGE	0.6640					
LINE SCAN PHI	90					
MODEL EMISSIVITY	0.92					
REF EMISSIVITY	0.96					
WINDOW FACTOR	0.840					

TYPICAL INFRARED SCANNING DATA

ARO, INC., AEDC DIVISION
A SVERDRUP CORPORATION COMPANY
VON KARMAN GAS DYNAMICS FACILITY (VKF)
ARNOLD AIR FORCE STATION, TENNESSEE
AEDC/DOTR AERODYNAMIC HEATING
PROJECT V418-Y5

DATE COMPUTED 31-OCT-78
TIME COMPUTED 07:20
DATE RECORDED 19-OCT-78
TIME RECORDED 1: 8: 7

RTV INSERT

IR TEMPERATURE RECORD -- TWALL/INITIAL TEMP
DELTA TIME 34.26 SEC
INITIAL TEMP 538.7 DEG R
*** POINT ***

GROUP 8
BURST 5 FRAME 5

LINE	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
68	1.086	1.085	1.082	1.081	1.082	1.080	1.080	1.081	1.081	1.081	1.081	1.082	1.083	1.081	1.081	1.082	1.082	1.082	1.080	1.081
69	1.089	1.088	1.084	1.084	1.084	1.082	1.081	1.082	1.083	1.082	1.082	1.082	1.082	1.081	1.083	1.082	1.083	1.082	1.085	1.084
71	1.087	1.087	1.086	1.086	1.086	1.088	1.087	1.084	1.082	1.083	1.083	1.082	1.081	1.082	1.081	1.082	1.082	1.081	1.081	1.083
74	1.078	1.076	1.077	1.074	1.074	1.074	1.072	1.073	1.073	1.071	1.072	1.070	1.071	1.072	1.073	1.072	1.070	1.069	1.070	1.068
77	1.086	1.085	1.083	1.082	1.082	1.083	1.081	1.079	1.078	1.079	1.079	1.078	1.078	1.077	1.076	1.075	1.073	1.073	1.073	1.071
80	1.083	1.082	1.081	1.082	1.081	1.081	1.079	1.078	1.079	1.079	1.078	1.077	1.076	1.077	1.076	1.077	1.072	1.072	1.070	1.071

LINE	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40
68	1.083	1.081	1.080	1.078	1.079	1.077	1.076	1.075	1.075	1.075	1.073	1.072	1.072	1.072	1.069	1.068	1.069	1.070	1.068	1.070
69	1.084	1.082	1.083	1.083	1.081	1.079	1.078	1.079	1.077	1.077	1.074	1.073	1.074	1.072	1.071	1.071	1.071	1.071	1.072	1.082
71	1.082	1.084	1.082	1.083	1.081	1.080	1.079	1.080	1.078	1.077	1.075	1.076	1.075	1.075	1.072	1.074	1.075	1.081	1.092	1.101
74	1.067	1.067	1.068	1.064	1.064	1.066	1.066	1.067	1.067	1.068	1.070	1.069	1.070	1.069	1.071	1.072	1.076	1.081	1.090	1.095
77	1.072	1.071	1.072	1.071	1.071	1.071	1.070	1.069	1.069	1.069	1.069	1.070	1.068	1.069	1.068	1.070	1.071	1.074	1.083	1.096
80	1.069	1.069	1.067	1.067	1.066	1.066	1.064	1.066	1.064	1.066	1.066	1.066	1.066	1.066	1.063	1.067	1.068	1.069	1.068	1.068

LINE	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60
68	1.079	1.090	1.101	1.108	1.112	1.112	1.114	1.113	1.115	1.114	1.113	1.115	1.114	1.113	1.111	1.110	1.107	1.103	1.096	1.088
69	1.097	1.104	1.108	1.113	1.115	1.116	1.117	1.117	1.117	1.117	1.117	1.117	1.117	1.116	1.115	1.113	1.113	1.108	1.103	1.099
71	1.107	1.113	1.115	1.117	1.117	1.120	1.120	1.120	1.121	1.123	1.121	1.122	1.120	1.120	1.119	1.118	1.115	1.112	1.108	1.104
74	1.100	1.103	1.105	1.108	1.110	1.112	1.114	1.115	1.117	1.117	1.118	1.117	1.118	1.117	1.116	1.115	1.113	1.109	1.106	1.103
77	1.106	1.111	1.115	1.117	1.119	1.121	1.121	1.122	1.122	1.123	1.124	1.124	1.124	1.123	1.123	1.120	1.120	1.119	1.116	1.113
80	1.068	1.074	1.084	1.097	1.106	1.112	1.114	1.116	1.116	1.118	1.117	1.117	1.116	1.116	1.115	1.112	1.106	1.099	1.093	1.088

LINE	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80
68	1.083	1.080	1.078	1.075	1.077	1.075	1.074	1.074	1.073	1.072	1.071	1.069	1.069	1.067	1.066	1.063				
69	1.091	1.083	1.079	1.078	1.077	1.075	1.076	1.074	1.074	1.073	1.070	1.070	1.071	1.069	1.066	1.064				
71	1.100	1.094	1.086	1.082	1.079	1.077	1.075	1.075	1.074	1.073	1.071	1.071	1.070	1.069	1.068	1.067				
74	1.100	1.097	1.093	1.085	1.082	1.078	1.077	1.075	1.073	1.073	1.072	1.071	1.068	1.067	1.067	1.064				
77	1.107	1.099	1.092	1.088	1.084	1.083	1.082	1.081	1.079	1.077	1.076	1.074	1.071	1.070	1.068	1.067				
80	1.085	1.084	1.083	1.084	1.083	1.082	1.082	1.081	1.080	1.078	1.074	1.073	1.072	1.069	1.066	1.064				

TYPICAL INFRARED SCANNING DATA

ARO, INC., AEDC DIVISION
A SVERDRUP CORPORATION COMPANY
VON KARMAN GAS DYNAMICS FACILITY (VKF)
ARNOLD AIR FORCE STATION, TENNESSEE
AEDC/DOTR AERODYNAMIC HEATING
PROJECT V41B-Y5

DATE COMPUTED 31-OCT-78
TIME COMPUTED 07:20
DATE RECORDED 19-OCT-78
TIME RECORDED 1: 8: 7

RTV INSERT

PAGE 3

IR HEAT TRANSFER COEFFICIENT = H(.9TO)/HRFR
DELTA TIME 34.26 SEC
HRFR= 0.657E-02
*** POINT ***

GROUP 8
BURST 5 FRAME 5

LINE	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
68	0.074	0.073	0.070	0.069	0.070	0.068	0.068	0.069	0.069	0.069	0.069	0.070	0.071	0.069	0.069	0.070	0.070	0.070	0.068	0.069
69	0.076	0.075	0.072	0.072	0.072	0.070	0.069	0.070	0.071	0.070	0.070	0.070	0.070	0.069	0.071	0.070	0.071	0.070	0.073	0.072
71	0.074	0.074	0.074	0.074	0.074	0.075	0.074	0.072	0.070	0.071	0.071	0.070	0.069	0.070	0.069	0.070	0.070	0.069	0.069	0.071
74	0.066	0.065	0.066	0.063	0.063	0.063	0.061	0.062	0.062	0.060	0.061	0.059	0.060	0.061	0.062	0.061	0.059	0.058	0.059	0.057
77	0.074	0.073	0.071	0.070	0.070	0.071	0.069	0.067	0.066	0.067	0.067	0.066	0.066	0.066	0.065	0.064	0.062	0.062	0.062	0.060
80	0.071	0.070	0.069	0.070	0.069	0.069	0.067	0.066	0.067	0.067	0.066	0.066	0.065	0.066	0.065	0.066	0.061	0.061	0.059	0.060

LINE	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40
68	0.071	0.069	0.068	0.066	0.067	0.066	0.065	0.064	0.064	0.064	0.062	0.061	0.061	0.061	0.058	0.057	0.058	0.059	0.057	0.059
69	0.072	0.070	0.071	0.071	0.069	0.067	0.066	0.067	0.066	0.066	0.063	0.062	0.063	0.061	0.060	0.060	0.060	0.060	0.061	0.070
71	0.070	0.072	0.070	0.071	0.069	0.068	0.067	0.068	0.066	0.066	0.064	0.065	0.064	0.064	0.061	0.063	0.064	0.069	0.079	0.087
74	0.056	0.056	0.057	0.054	0.054	0.055	0.055	0.056	0.056	0.057	0.059	0.058	0.059	0.058	0.060	0.061	0.065	0.069	0.077	0.081
77	0.061	0.060	0.061	0.060	0.060	0.060	0.059	0.058	0.058	0.058	0.058	0.059	0.057	0.058	0.057	0.059	0.060	0.063	0.071	0.083
80	0.058	0.058	0.056	0.056	0.055	0.055	0.054	0.055	0.054	0.055	0.055	0.055	0.055	0.055	0.053	0.056	0.057	0.058	0.057	0.057

LINE	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60
68	0.067	0.077	0.087	0.093	0.097	0.097	0.099	0.099	0.100	0.099	0.099	0.100	0.099	0.098	0.096	0.096	0.092	0.089	0.083	0.075
69	0.084	0.090	0.094	0.098	0.100	0.101	0.102	0.102	0.102	0.102	0.102	0.102	0.102	0.101	0.100	0.099	0.098	0.094	0.089	0.085
71	0.092	0.098	0.100	0.102	0.102	0.104	0.104	0.105	0.106	0.107	0.106	0.107	0.105	0.104	0.104	0.103	0.100	0.097	0.094	0.090
74	0.086	0.088	0.091	0.093	0.096	0.097	0.099	0.100	0.102	0.102	0.103	0.102	0.103	0.102	0.101	0.100	0.099	0.095	0.092	0.089
77	0.092	0.096	0.100	0.102	0.104	0.106	0.106	0.107	0.107	0.108	0.109	0.109	0.109	0.108	0.108	0.105	0.104	0.104	0.101	0.098
80	0.057	0.063	0.072	0.084	0.092	0.097	0.099	0.101	0.101	0.103	0.102	0.102	0.101	0.101	0.100	0.097	0.092	0.085	0.079	0.075

LINE	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80
68	0.071	0.068	0.066	0.064	0.066	0.064	0.063	0.063	0.062	0.061	0.060	0.058	0.058	0.056	0.055	0.053				
69	0.078	0.071	0.067	0.066	0.066	0.064	0.065	0.063	0.063	0.062	0.059	0.059	0.060	0.058	0.055	0.054				
71	0.086	0.080	0.074	0.070	0.067	0.066	0.064	0.064	0.063	0.062	0.060	0.060	0.059	0.058	0.057	0.056				
74	0.086	0.084	0.079	0.073	0.070	0.066	0.066	0.064	0.062	0.062	0.061	0.060	0.057	0.056	0.056	0.054				
77	0.092	0.085	0.079	0.075	0.072	0.071	0.070	0.069	0.067	0.066	0.065	0.063	0.060	0.059	0.057	0.056				
80	0.073	0.072	0.071	0.072	0.071	0.070	0.070	0.069	0.068	0.066	0.063	0.062	0.061	0.058	0.055	0.054				

TYPICAL INFRARED SCANNING DATA

ARO, INC. - AEDC DIVISION
A SVERDRUP CORPORATION COMPANY
VON KARMAN GAS DYNAMICS FACILITY
ARNOLD AIR FORCE STATION, TENNESSEE
AEDC/DOTR AERO HEATING

DATE COMPUTED 27-NOV-78
TIME COMPUTED 14:52:16
DATE RECORDED 19-OCT-78
TIME RECORDED 2: 7:53
PROJECT NUMBER V418-Y5

INSTRUMENTED PANEL

GROUP	MACH	CONFIGURATION	ALPHA-MODEL (DEG)	ROLL-MODEL (DEG)	PO (PSIA)	TO (DEGR)
10	8.00	N00.0T000	-0.01	180.18	871.1	1347.7

T-INF (DEGR)	P-INF (PSIA)	Q-INF (PSIA)	V-INF (FT-SEC)	RHO-INF (SLUG/FT3)	MU-INF (LB-SEC/FT2)	RE/FT (FT-1)	HREF (R= 1.0000FT)
97.66	0.09	3.997	3876.	7.664E-05	7.858E-08	3.780E+06	6.56E-03

GAGE NO	TW DEG,R	TI DEG,R	QDOT BTU/FT2-SEC	H(TO) BTU/FT2-SEC-R	H(TO)/ HREF	H(.9TO) BTU/FT2-SEC-R	H(.9TO)/ HREF
1	541.1	534.2	1.596	1.979E-03	0.3016	2.376E-03	0.3621
2	540.2	533.9	1.434	1.776E-03	0.2706	2.132E-03	0.3248
3	538.2	533.9	0.957	1.182E-03	0.1801	1.418E-03	0.2161
4	538.0	533.6	0.950	1.174E-03	0.1789	1.408E-03	0.2146
5	537.9	533.1	1.016	1.255E-03	0.1912	1.506E-03	0.2294
6	538.7	532.6	1.272	1.572E-03	0.2396	1.886E-03	0.2874
7	540.1	532.3	1.733	2.146E-03	0.3270	2.576E-03	0.3925
8	540.8	531.9	1.911	2.368E-03	0.3608	2.843E-03	0.4332
9	541.2	531.7	2.125	2.635E-03	0.4016	3.164E-03	0.4821
10	539.6	531.8	1.706	2.111E-03	0.3217	2.534E-03	0.3861
11	541.2	532.4	1.891	2.344E-03	0.3572	2.815E-03	0.4289
12	541.3	533.0	1.795	2.226E-03	0.3392	2.673E-03	0.4073
13	541.7	533.2	1.771	2.198E-03	0.3349	2.639E-03	0.4021
15	542.1	534.0	1.764	2.189E-03	0.3336	2.629E-03	0.4006
16	542.1	534.3	1.636	2.031E-03	0.3094	2.439E-03	0.3716
17	541.6	534.5	1.545	1.916E-03	0.2920	2.301E-03	0.3507
18	541.2	534.4	1.422	1.763E-03	0.2686	2.116E-03	0.3225
19	541.2	534.3	1.443	1.790E-03	0.2727	2.149E-03	0.3275
20	541.7	534.7	1.596	1.981E-03	0.3018	2.379E-03	0.3624
21	541.8	534.7	1.532	1.901E-03	0.2896	2.283E-03	0.3478
24	540.7	535.1	1.205	1.493E-03	0.2276	1.793E-03	0.2732
25	541.1	534.9	1.335	1.655E-03	0.2521	1.987E-03	0.3027

GAGE NO	TCASE DEG,R	TW DEG,R	QDOT BTU/FT2-SEC	H(TO) BTU/FT2-SEC-R	H(TO)/ HREF	H(.9TO) BTU/FT2-SEC-R	H(.9TO)/ HREF
22	535.0	544.1	1.741	2.167E-03	0.3302	2.603E-03	0.3967
23	536.5	540.4	1.853	2.296E-03	0.3498	2.756E-03	0.4199

TC-NO	TW	DTWDT	QDOT	H(TO)	H(TO)/HREF	H(.9TO)	H(.9TO)/HREF
26	553.5	10.376	1.468	1.848E-03	0.2816	2.226E-03	0.3392
27	554.1	10.304	1.458	1.837E-03	0.2799	2.213E-03	0.3372
28	556.3	11.460	1.623	2.051E-03	0.3126	2.472E-03	0.3767
29	554.9	11.041	1.563	1.972E-03	0.3004	2.375E-03	0.3620
30	553.6	10.957	1.550	1.952E-03	0.2974	2.351E-03	0.3583

TYPICAL DISCRETE GAGE DATA